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SEMICONDUCTOR SURFACE AND SEMICONDUCTOR-ELECTROLYTE INTERFACE STUDY USING ACOUSTIC SURFACE WAVE

FINAL REPORT

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by

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Professor of Electrical Engineering
Department of Electrical, Computer, and Systems Engineering

August 1981

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The research work can be broadly calssified into four categories: 1) a new method for the determination of electrical surface properties of semiconductors using acoustic surface wave delay lines, 2) a new method for the determination of electrical properties of semiconductor-electrolyte interface, 3) optical signal processing using surface acousto-optic interaction, and 4) studies on hot electron properties of semiconductors. The method of surface property determination is sensitive and simple and requires no physical contact with semiconductor surface. Both experimental and

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20. Abstract (continued)

theoretical work related to this technique have been performed.

In the past years significant progress has been made including publication of thirty one papers and thirty one presentations in national and international meetings and two reports. Some of the important results obtained are:

a) The SAW probing technique for electrical characterization of semiconductors has been performed at low temperatures down to 77°K. Results obtained with GaAs agree with the theoretical expectations.

b) Oxides have been adodically grown on GaAs and interface properties are being evaluated using the SAW probe.

c) The activation of ion-implanted impurities in silicon by thermal annealing is being monitored by the SAW probing technique.

d) Numerical computations of the transverse acoustoelectric voltage (TAV) have been performed which can be used to quantitatively evaluate the semiconductor properties non-destructively from the experimental TAV data.

e) In connection with semiconductor-electrolyte interface study, the electrical properties of CdS-$NiCl_2$ interface have been determined using the surface acoustic wave technique. Some interface states within the bandgap have been identified and found to influence the electrical properties significantly.

f) In the field of optical signal processing, different configurations for real time correlators using SAW-optic interaction have been considered.

g) The transient response of semiconductors under hot electron condition has been calculated for an inversion layer in silicon and bulk compound semiconductors.

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ABSTRACT

The research work can be broadly classified into four categories: 1) a new method for the determination of electrical surface pro-erties of semiconductors using acoustic surface wave delay lines, 2) a new method for the determination of electrical properties of semiconductor-electrolyte interface, 3) optical signal processing using surface acousto-optic interaction, and 4) studies on hot electron properties of semiconductors. The method of surface property determination is sensitive and simple and requires no physical contact with semiconductor surface. Both experimental and theoretical work related to this technique have been performed.

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f) In the field of optical signal processing, different configurations for real time correlators using SAW-optic interaction have been considered.

g) The transient response of semiconductors under hot electron condition has been calculated for an inversion layer in silicon and bulk compound semiconductors.

1. INTRODUCTION

The research studies under this contract can be broadly classified into four main categories:

i) determination of electrical surface properties of semiconductors

ii) determination of electrical properties of semiconductor-electrolyte interface

iii) related optical signal processing and

iv) hot electron studies.

The significant progresses made in these categories will be discussed in the next section. The details have been presented in the following thirty one papers and thirty one presentations in the national and international meetings. Three students have obtained their doctoral degree, two more are in the process of getting it and numerous students have obtained their Masters degree partially funded by this contract.

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4. P. Das, H. Estrada-Vazquez and R. Webster, "Transverse Acousto-electric Voltage (TAV) Spectroscopy of High Resistivity GaAs", J. Appl. Phys., Vol. 50, pp. 4942-4950, 1979.

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5. J. Scott Moore and P. Das, "The Transient Response of Hot Electrons in Quasi-Two-Dimensional Semiconductors", J. Appl. Phys., 50(12), pp. 8082-8086.

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1. J. Scott Moore and P. Das, "Hot Electron Effects in Quasi-Two Dimensional Semiconductors", presented at the American Physical Society March Meeting, New York City, March 24-28, 1980.

2. K. Varahramyan and P. Das, "Study of Electrical Activation in Ion-Implanted GaAs", presented at the American Physical Society Meeting, March 16-29, 1981.

3. P. Das, M. K. Roy, R. T. Webster and K. Varahramyan, "Nondestructive Evaluation of Si Wafers using SAW", presented at the Ultrasonics Symposium, New Orleans, Sept. 26-28, 1979.

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5. P. Das, "Transverse Acoustoelectric Voltage (TAV) Spectroscopy of Gallium Phosphide, Indium Arsenide and Cadmium Sulphide-Nickel Chloride", presented at the Sixth Annual Conference, Physics of Compound Semiconductor Interfaces, Monterrey, Calif. Jan. 30-Feb. 2, 1979.

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29. D. Schumer, L. Pearce and P. Das, "Influence of Light Polarization on Performance of $LiNbO_3$ Surface Wave Acousto-optic Devices", presented at the 1975 Annual Meeting of the Optical Society of America, Boston, Massachusetts, October 1975.

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31. P. Das and D. Schumer, "Signal Processing Using Surface Acousto-Optic Interaction in $LiNbO_3$", presented in the IEEE Symposium on Applications of Ferroelectrics, Alburquerque, New Mexico, June 1975.

Reports*

1. D. Schumer and P. Das, "Acousto-optic Interaction in Surface Acoustic Waves and its Application to Real Time Signal Processing", ONR Technical Report, December 1977, 148 pages.

2. H. Gilboa and P. Das, "Nondestructive Evaluation of Electrical Properties of Semiconductors using SAW," ONR Technical Report, June 1977, 187 pages.

Patents

1. U. S. Patent No. 4,093,976, "Image Scanning Using SAW Devices".

2. Patent Pending, "Multiple Buried Channel Charge Coupled Device".

2. RESEARCH

2.1 DETERMINATION OF ELECTRICAL SURFACE PROPERTIES OF SEMICONDUCTORS USING NON-CONTACT SAW PROBING

A new technique has been developed to determine the electrical surface properties of semiconductors using surface acoustic wave delay line. The technique is unique in the sense that there is no physical contact with the semiconductor surface. Using this method, it is possible to determine the "virgin" surface properties rather than the surface properties of the interface between the semiconductors and another material.

The surface acoustic wave is excited by an interdigital transducer fabricated directly on the surface of a piezoelectric crystal. These waves propagate in the vicinity of the surface with a velocity slightly lower than the bulk shear wave velocity of the crystal. The mechanical motions are confined to the surface of the crystal decaying exponentially within the crystal away from the surface. The surface acoustic wave is accompanied by a propagating electric field. Though this electric field

*Copies of the reports are available upon request.

is also confined near the surface it exists both inside and outside the crystal. The decay constant of the electric field outside the surface is of the order of the surface acoustic wave wavelength. When a semiconductor sample is placed in the proximity of a surface acoustic wave delay line, this decaying electric field interacts with the carriers in the semiconductor surface. Inside the semiconductor, the electric field decays within a Debye length from the surface, so for short Debye length semiconductors, the interaction takes place mainly on the surface. The manifestation of this interaction is the appearance of the the transverse acoustoelectric voltage (TAV), attenuation of the delay line output, a change in SAW velocity, and a convolution voltage. The last one appears only when two inputs are applied simultaneously at the two ports of the delay line and has a frequency twice that of the input signal. By studying the variation of these outputs as a function of time while the semiconductor is illuminated with different wavelengths and intensities of light or with a DC voltage across the structure, the sample temperature being accurately controlled, valuable information is obtained about the semiconductor surface.

In general, the delay line is Y-cut, Z-propagating lithium-niobate, with interdigital transducers deposited at each end. A mechanical arrangement allows placement of the semiconductor in the proximity of the delay line with a uniform air gap. Electrical contact is made at the back of the semiconductor by metal deposition or with a metal plate. The interdigital transducers provide input-output ports for the delay line. The metal contact allows monitoring of the acoustoelectric voltage and can be used to bias the semiconductor surface. Provision is made to illuminate the semiconductor surface with monochromatic radiation of variable intensity and wavelength. The entire structure can be immersed in a dewar for accurate control of temperature.

Using delay line attenuation measurements with semiconductor biasing, it is possible to determine the distribution of the density of surface states (cm^{-2} eV^{-1}) and majority carrier capture cross section in the energy gap. Photoconductivity measurements can be performed which yield carrier lifetime data in Si, GaAs, and CdS. Through spectroscopy measurements deep level surface states have been observed in GaAs. These techniques are being continuously refined and expanded as our understanding of the nature of the surface acoustic wave-semiconductor interaction deepens.

The properties which have been determined using this technique are shown in Table I.

Recently, the following specific studies have been performed in this area:

a) The temperature dependence of deep levels in GaAs has been evaluated by performing TAV spectroscopy at temperatures between 300^{o}K and 77^{o}K.

b) Oxides have been grown on GaAs by anodizing the single crystal semiconductor in an acid-glycol bath. The semiconductor is nondestructively evaluated before and after anodization to determine the effects of the process on surface electrical properties.

c) Following implantation in a silicon substrate, impurities must be activated by either thermal or laser annealing. The SAW probing technique has been used to nondestructively monitor the effectiveness of the thermal annealing cycle by measuring the

TABLE I

NDE OF SEMICONDUCTORS USING SAW

SEMICONDUCTOR PROPERTY	SAW MEASUREMENT	VARIABLES	REQUIRED ANALYSIS
1. Conductivity	TAV	-	Calibrate theoretical plots for each semiconductor
2. Type of Majority Carrier Near Surface	TAV	-	The polarity of TAV indicates carrier type: Positive for n-type, negative for p-type
3. Emission time constant, capture cross section	Attenuation	Scan the semiconductor with dc bias voltage while applying an additional bias pulse.	Through analysis of the effect of the pulse at each bias point obtain capture cross-section and surface state distribution as a function of energy.
4. Trap Levels	TAV	Shine monochromatic light.	Observe peaks and valleys in the spectral response and correlate them with carrier transitions.
5. Surface State Density	Attenuation	Use dc bias voltage to scan the semiconductor surface from accumulation to depletion	Compare scans with theoretical plots to obtain flat band voltage and surface state density.
6. Photoconductivity Response Time	Attenuation	Shine pulsed light. Use dc bias voltage to deplete or accumulate the semiconductor surface.	Measure the time constant caused by the light pulse. The effects of bulk and surface recombination can be separated by comparing data obtained under various bias conditions.
7. Carrier Generation Rate	Attenuation	Drive the semicon- from accumulation to deep depletion by switching the dc bias voltage.	Observe the recovery of the attenuation. This time constant is the inverse of the generation rate.
8. Annealing Effectiveness (Laser or Thermal)	TAV	-	Observe the change in conductivity and type of majority carrier. These indicate the extent of annealing.
9. Epitaxial Layer Properties	TAV or Attenuation	-	SAW measurements are confined to a Debye length. Thus, the surface layer properties are obtained with little interference from the bulk.

TAV after various heat treatments. For example, when a P-type impurity has been implanted in an n-type sample, the TAV changes sign when the sample is activated.

d) Several refinements have been made in the theoretical model of the SAW-semiconductor interaction. Plots of the TAV as a function of conductivity have been obtained for various semiconductors including Si, GaAs, GaP, InAs and CdS. The plots are used to assign guantitative values to the semiconductor parameters measured in the SAW experiments.

2.2 DETERMINATION OF ELECTRICAL PROPERTIES OF SEMICONDUCTOR-ELECTROLYTE INTERFACE USING SAW PROBING

Compound semiconductor technology, especially GaAs, has certain advantages over silicon technology, such as higher frequency operation of integrated circuits, provided insulating layers with good dielectric and interface properties can be grown on compound semiconductors. One approach to the growth of oxide layer on GaAs is by anodization in a solution of glycol and water. Controlled native oxide layer on GaAs has been grown by this process and its application to surface passivation, MOS technology, planar integration and device fabrication processes such as masking and controlled etching have been discussed. However, even the best anodic oxides grown up to date are far from the stage where one can make reliable devices routinely. The basic problem seems to be the incomplete understanding of the electrical properties of the semiconductor-electrolyte interface.

Semiconductor-electrolyte junction devices can also be used as photovoltaic energy converters with moderate efficiency. The most attractive feature of this kind of solar cell is the potentially low manufacturing cost. There are, however, several obstacles in the development of these cells. A most important one is the stability of the cell which is related to the photo-corrosion of the semiconductor interface. Thus, the success of the semiconductor-electrolyte solar cell depends on our understanding of the interface with special attention given to the electrical and corrosion properties.

We have developed a contactless technique of determining electrical properties of the semiconductor-air interface using a surface acoustic wave (SAW) probe. This technique has been extended to study the semiconductor-electrolyte interface. Some of the specific properties which are expected to be determined are surface conductivity, surface mobility, space charge layer width, surface potential, and changes in the locations in the energy gap, densities and capture cross sections of the surface states. One important advantage of this method of interface characterization is that the electrical properties can be determined as the anodization is progressing and without removing the sample from the cell.

Recently, TAV spectroscopy of the CdS-$NiCl_2$ interface has been expanded to include two beam spectroscopy. With this technique, the sample is illuminated with monochromatic light of various wavelengths while a second source of fixed wavelength is used to stimulate an interface level. This two beam method can clarify the effect that a particular level has on the electrical properties of the interface. For example, whether the level is an electron donor or an acceptor.

2.3 OPTICAL SIGNAL PROCESSING USING SURFACE ACOUSTIC WAVES

In the field of optical signal processing, different configurations for real time correlators using SAW-optic interaction have been considered. The details can be obtained from papers 3, 9, 12, 15, 16, 23 and 29.

2.4 HOT ELECTRON STUDIES (Papers No. 5, 14, 21, 24)

The behavior of hot electrons in quasi-to-dimensional semiconductors has been modeled, assuming a displaced Maxwellian distribution function applied to a <100> inversion layer in silicon. Under a high electric field, energy levels become grouped into subbands, so that motion of carriers perpendicular to the surface becomes quantized; thus, the energy, momentum and population transfer relaxation times appropriate to the individual levels must be considered in the calculations, along with their relation to velocity overshoot. Previous work has been performed under the assumption that intervalley scattering is a local phenomenon, i.e., a function only of electron temperature of the initial valley. In this work, this assumption was relaxed, and the intervalley coupling of electron temperature is taken into account. dc and transient response characteristics for both uncoupled and coupled models have been calculated, and the results compared.

A theory of transport of hot electrons in quasi-two-dimensional III-V compounds has been derived, but numerical considerations have prevented its complete treatment on computer, at least with the approach used for silicon inversion layers. Further work, based on Monte Carlo techniques will, hopefully, allow complete calculation of dc and transient response characteristics, along with the extension of this theory to $GaAs/GaAl_xAs_{1-x}$ superlattices.

A theory for transport of hot electrons in bulk III-V compounds was used as a basis for computer modeling of these semiconductors, the treatment being similar in scope to that used for silicon inversion layers. Velocity overshoot was observed in these compounds, due solely to intervalley repopulation, unlike silicon inversion layers, where the cause is differences between energy and momentum relaxation rates. In all cases, overshoot is a very fast phenomenon, taking place at about 10^{-12} sec.

The treatment for bulk III-V compounds was easily extended to ternary and quaternary alloys of III-V compounds. dc and transient response calculations for III-V compounds and their alloys yielded, in most cases, the same principal features of intervalley repopulation and negative differential mobility, illustrating potentially significant implications toward operation of devices using these semiconductors.

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